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On the effectiveness of time and date-based sun positioning solar collector in tropical climate: A case study in Northern Peninsular Malaysia

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ABSTRACT

This paper provides detailed information on the developed hardware and software for sun tracking mechanism and shows the effectiveness of utilizing time and date-based sun positioning solar collector system in tropical climate. The sun positioning system is based on the calculated azimuth and altitude at location E100°11′, N6°26′ in Northern Peninsular Malaysia where the climate is categorized as tropical climate. The system has two axes tracking with accuracy of 1° controlled by a programmable logic controller (PLC). The field test has been done during a sunny and clear day, cloudy day and, heavy overcast and rainy day in which the results show that the improvement in the generated power of 91.97%, 122.71% and 90.42%, respectively, as compared with the fixed horizontal system.

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1. Introduction

Renewable energy (RE) is the solution for a sustainable, clean and cheaper energy. Current state and prospects of RE in Malaysia is promising [1–4]. Solar energy particularly is abundant, and the potential in electricity generation from solar energy in Malaysia is suitable and are among the highest worldwide [5–8]. Solar PV systems, in particular, are still in the going for full utilization despite the government efforts in enhancing the current incentives through several policies and programs [9–12]. However, currently, the available PV systems in Malaysia are stand alone PV. Although the Malaysian climate is characterized by heavy rainfall, high temperature and high relative humidity of greater

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Nomenclature

I_D	Direct irradiance
I_{DN}	Direct normal to surface irradiance
θ_i	Incidence angle
I_{ext}	Extraterrestrial irradiance
I_c	Solar constant
N	Number of days in a year
α	Solar altitude angle
φ	Local latitude
δ	Solar declination angle
ω	Local hour angle
γ	Solar azimuthal angle

than 60%, a drawback to solar PV energy collection, the northern state in Malaysia is among the location with the highest potential of high annual average daily global solar radiation. Malaysia, in general, has an average of 6 h sunshine per day and maximum of 8.7 h average per day in January with a high average ambient temperature ranging from 26 °C to 32 °C annually [13]. Based on previous studies, solar powered devices are sufficient for operation with average daily solar radiations between 4.21 kW h m^{-2} to 5.56 kW h m^{-2} [2]. The yearly average global solar irradiation distributions in Malaysia vary with the highest value of 1900 kW h m^{-2} in Kota Kinabalu followed by a district in Northern Malaysia state, Bayan Lepas with 1809 kW h m^{-2} as in Fig. 1. Estimated, with only 0.6% PV panel covering Peninsular Malaysia, electricity demand in 2007 of 86.5 TW h can be fulfilled [14].

Solar tracking is a proven method to significantly improve the energy collected from the sun compared to fixed panel. Different sun tracking systems and approaches has been used to track the dun accordingly. There are various approaches to track the sun and can be categorized into 3 large groups based on the method of control which are; closed loop, open-loop and hybrid. Generally, closed loop systems use photo sensors in its tracking system while open loop system involved a mathematical calculation of the sun's position without photo sensing. Hybrid, in the meantime, is the combination of both closed and open loop systems. The advantage of an open loop system compared to the closed loop system is; it is not dependant on the weather condition and can work independently despite of cloudy conditions where most of conventional closed-loop systems fail to work properly under non uniform insolation conditions [15]. Moreover, the drawback of a closed loop system is; it requires additional hardware and complex control systems and actuators. In this climate, where cloud formations are frequent, open loop system is more suitable thus power is not wasted in frequent movement of the actuator as a result of the photo sensors used. In the meantime, in comparison to closed-loop and hybrid system, open loop is chosen since it is more cost effective and well suited to this tropical climate.

Generally, the sun tracking system is categorized as a mechatronic system. A single axis sun-tracking system consists of one controlling motor with varying azimuth angle and a fixed-tilt angle, while a dual-axes sun-tracking system has two controlling motors varying in azimuth angle and altitude-angle of the sun. The dual axes are the best system in all weather conditions even in tropical regions [16]. In previous studies, single axis tracking was implemented in systems and simply put, minimized the power consumption yet improved the solar energy yield. One system uses discrete two-positional changes in azimuth angle in its tracking system [17], while, many others use either a closed-loop system or an open-loop system to control the movement of the motor [18–20].

A dual-axes tracking system, however, is more popular than the single-axis since it produces more energy. The application varies from photovoltaics (PV), solar collector and even to control the effective orientation of a pyrheliometer. Sungur designed an open loop PV system based on the calculation of the sun each hour of the day. The movement is divided into different time slices from

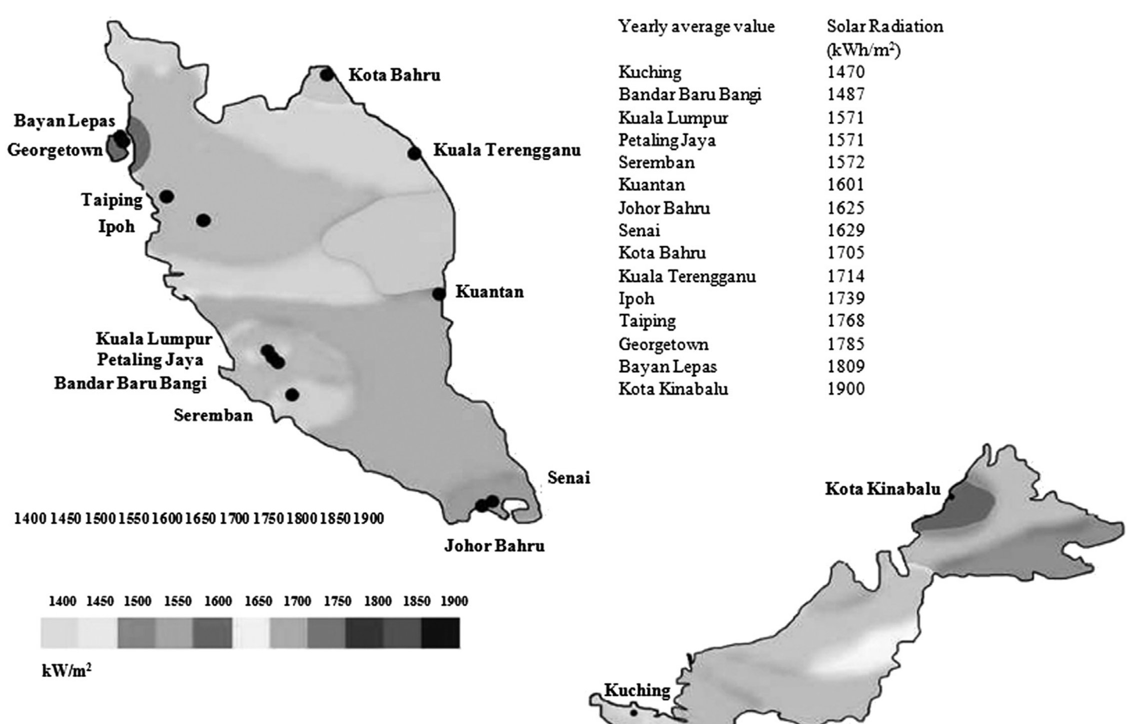


Fig. 1. Solar radiation distributions in Malaysia [14].

sunrise to sunset and the results showed that 42.6% more energy was obtained compared to a fixed tilted panel [21]. In another research, a mechanical scheme was proposed for an open-loop dual-axes tracking PV system. The movements of the controlling motors were controlled using a computer and database. A DC motor is used for altitude tracking and an AC motor is used for azimuth tracking. The reason behind the use of the powerful AC motor is to enable accommodation of more PV modules [22]. Yet in another research, a parabolic solar cooker (PSC) system was designed and constructed to operate in an open-loop system where the daylight hours were divided into a few time intervals, in which the motors were instructed to work or idle using two PLCs. The research claimed to reduce cost and maintenance and only consumed 3% of the power saved and produced gain of up to 48.73% compared to the fixed tilted system [23–25].

In another experiment, a closed-loop system is used to control the pointing of a pyrheliometer using four quadrant photo sensors and computing programs. This claimed simple and cheap system, changes modes and calculates the position of the sun under cloudy conditions [26–28]. In other work, a solar dish system using computer tracking based on picture processing of bar shadow is implemented. Using a special camera for picture processing, this system is independent of geographical location and time [29]. In another work, a hybrid PV system that tracks the sun by using the solar position computer program, but changes to horizontal (H) positioned during cloudy condition was implemented. The system claimed that it minimized the size of the system, maximized both direct and diffuse irradiance and increased 50% more energy during cloudy days [30]. In another hybrid PV system, a feedback controller in a microprocessor is used to correct tracking errors made by the open loop mode. It is said to save the energy consumed in the driving motors [31].

2. Methodology

In this work, an open-loop two-axes sun tracking system with an angle controller was designed and constructed. The objectives of this research are to build an automatic time-based dual axes solar tracking system with an angle controller, utilizing a low cost mechanical structure and to compare the power produced from a fixed horizontal solar collector periodically, during various weather conditions. Since the main drawbacks of solar energy systems, commonly in a stand-alone tracking system are its initial cost and low energy conversion associated with the power consumed in the mechanism to move the tracker, it is therefore critical to maximize the power collected from the system whilst minimizing the power consumed. Thus, the hardware of this system is selected to achieve the best lightweight product, yet still strong and stable.

The programming of the controller was made based on precalculated angles of the sun at the selected location; the movements of the motors are based on the time in which the motors made 1° angle movements. The system moves in precisely staggered angle of 1° to reduce the solar radiation incidence angle in which it will contribute to a better sun′s ray collection. Detailed information on the design and programming are provided later in this paper. The field test of this system was done at location E100°11′, N6°26′ in Perlis, Northern Peninsular Malaysia for several days in December 2011 and January 2012 from 7:00 AM to 7:00 PM, in which, during those days the weather varied with clear and sunny days to rainy and cloudy days. During the experiment, two identical flat plate photovoltaics modules were mounted, one on the tracking surface and the other on the zenith facing non-tracking surface. Both systems were placed near to each other outdoors, in an open space with voltage and current data loggers attached to record the data once in every minute. Meanwhile, a few meters from the experiment′s setup, a weather recording system provided weather data synchronized with the data loggers. This work is very important in order to ensure the suitability of implementing the system to increase the collected power.

3. Solar radiation

Solar radiation is the main key in determining the amount of energy produced from a PV module. The rate in which solar energy reaches a unit area is called solar irradiance or insolation and the unit measurement is in W m^{-2}. The solar irradiance on a clear day is given by 1000 W m^{-2}. Initially, before the solar irradiance hit the atmosphere, it is called the solar constant, as it goes through the atmosphere; it is divided into several components before received by the solar array. The three main components are direct, diffuse and reflected and the summation of the components is known as the global irradiance.

During a clear and sunny day, 85–90% of the sun rays are mostly direct irradiance, I_D [32]. When the rays hit the PV surface, it decreases as the incidence angle, θ_i increases using the relationship between the direct normal irradiance, I_{DN} of the surface given in Eq. (3.1)

$$I_D = I_{DN} \cos\theta_i \tag{3.1}$$

Therefore, to increase the irradiance captured by the solar module, sun positioning is used to minimize the incidence angle.

4. Solar radiation on a horizontal surface

The quantity of solar energy fallen over a period of time is called solar radiation and is described in W h m^{-2} or J m^{-2}. At any time between sunrise and sunset, the apparent extraterrestrial solar radiation on a horizontal surface is calculated using Eq. (4.1) [33].

$$I_{ext} = I_c[1.0 + +0.033 \cos(360n/365)]\cos\theta_z \tag{4.1}$$

where I_c is the solar constant and n is the day of the year where $\cos\theta_z$ is given in Eq. (4.2).

$$\cos\theta_z = \cos\varphi \cos\delta \cos\omega + \sin\varphi \sin\delta \tag{4.2}$$

5. Sun position

In order to design a solar tracker, basic knowledge on the angle involved is important. Basically, the sun moves in accurate trajectories and its location in the sky corresponding to a location on the surface of the earth can be specified by two angles; the altitude angles, α and the azimuth angle, γ as demonstrated in Fig. 2. The solar altitude angle is defined as the angle between the sun′s position and the horizontal plane of the earth′s surface from the observer′s position (local horizon), where the maximum value of altitude angle is during noon. This angle can be calculated using Eq. (5.1) using information on local latitude, φ, solar declination angle, δ and local hour angle, ω [34].

$$\alpha = \sin^{-1}(\cos\varphi \times \cos\delta \times \cos\omega + \sin\varphi \times \sin\delta) \tag{5.1}$$

Another angle that describes the solar location is the solar azimuth angle and is defined as the angle between the vertical planes containing the solar disk and a line running due north using Eq. (5.2) using the solar altitude angle, α calculated in Eq. (5.1)

$$\gamma = \frac{\sin\alpha \times \sin\varphi - \sin\delta}{\cos\alpha \times \sin\varphi} \tag{5.2}$$

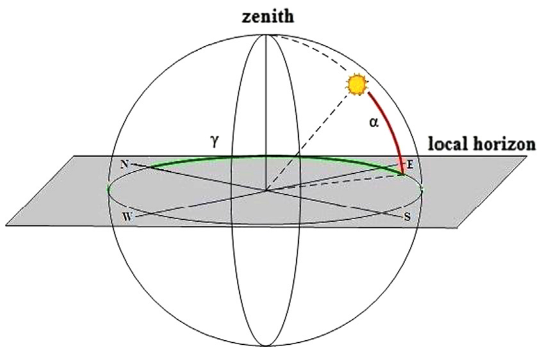


Fig. 2. Position of the sun.

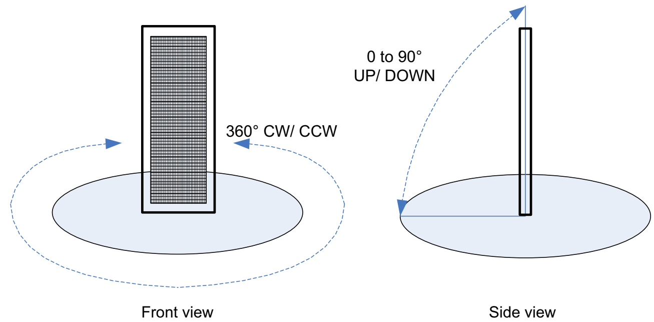


Fig. 3. Simplified structure.

6. Sun positioning mechanism

6.1. The structure design

The important tasks in designing sun positioning mechanism is the features of lightweight, cost effective and low energy consumption. Thus, the low cost and lightweight aluminum hollow is used. The both angle controller DC motors are selected to fulfill the features of low power and lightweight. The simplified structure is shown in Fig. 3 where the dimension is 140 cm × 90 cm × 110 cm. It is designed to be stable with a height of only 140 cm and a heavy base. The design is made to ease the movement of clockwise and counterclockwise and up and down both motors for altitude and azimuth tracking. Overall, the altitude tracking structure excluding the solar panel only weighted 0.34 kg while the azimuth tracking part together with the altitude tracking structure weighted 5.82 kg. This system can drive up to 2 sets of solar panel with the dimension and weight each of 33 cm × 128.5 cm and 7.02 kg, respectively.

6.2. Electromechanical Systems

In this work, the design of two-axes tracking were performed using an open loop method using a programmable logic controller (PLC) with 18 input/output points to control the movement and directions of both motors based on the program written in the PLC. The motor speeds were initially adjusted by setting the voltage supplied to both motors through two speed controller circuit. The voltage supplied to the altitude and azimuth tracking motors are set to a minimum value in which the tracking axis can move slowly, suitable for angle control, yet is still sufficient to move the load placed on the tracker. Therefore, the appropriate voltage supplied to the altitude and azimuth tracking motors are 3.91 V and 3.64 V, respectively. The program was written to turn on the supply to the motor based on the time taken to make a 1° rotation angle, in which, the time taken for the up and down altitude and clockwise and counter-clockwise azimuth motor are 1.9 s, 1.4 s, 1.1 s and 1.1. s, respectively. Then, based on the time taken for 1° angle rotation, the motor is turned on. The system structure of the PLC is connected as in Fig. 4. Since the connection of forward and reverse of both motors shared the same point, for security reason, the program is made to interlock, where only one is allowed to function at one time while the other is cut off.

6.3. Programming of angle controller

As solar angle values vary with time and location, the program was made to follow the sun's trajectories. Based on time, the motors are instructed to move for the mentioned time duration it takes to complete 1° movement, one after another based on the time gap between the increment angles. The time gap, in addition, varies throughout the day and is not the same throughout a year.

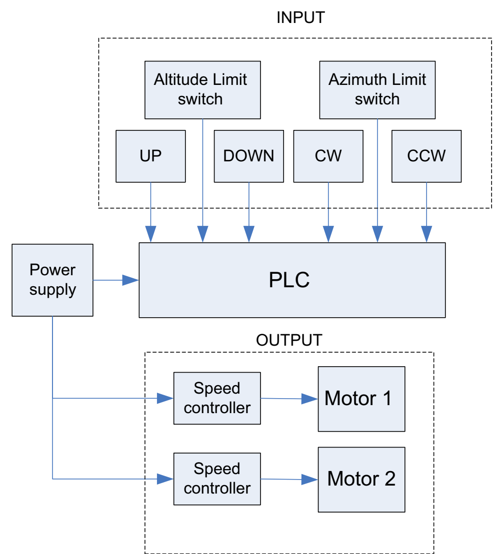


Fig. 4. System structure.

For example, in September, during the morning, 1° of increment in azimuth angle took about 35 min; the increment is faster during noon where in 1 min, the azimuth angle increases by 3°. Therefore, in 10 min almost 30° of azimuth increases. Similarly, the angles in altitude tracking also differ from time to time and the maximum value it reaches is different. The maximum altitude angle during April and September is 90°, while in December the maximum altitude angle during noon only reaches 60°. Furthermore, there are times where the sun's is in the North celestial pole, or in South celestial pole, which determines the movement of azimuth controlled motor either to rotate clockwise or counterclockwise as in Fig. 5. Therefore, taking into consideration such conditions, the program is made to follow the sun based on the movement they are made accordingly by 1°. A brief idea on the location of the sun hourly in a different celestial pole is given in Table 1.

7. Field test

The field tests were done during several days in December 2011 and January 2012 from 7:00 AM to 7:00 PM. Two identical flat plate photovoltaics modules were mounted on the two-axes tracking surfaces and zenith facing non-tracking surface, respectively. The rated electrical characteristics of the solar module are shown in Table 2, where the maximum power under standard test conditions is 38 W. The short circuit current and the open circuit voltage are 2.59 A and 22.2 V, respectively. During the experiment, a voltage and current data loggers were connected to both of the solar

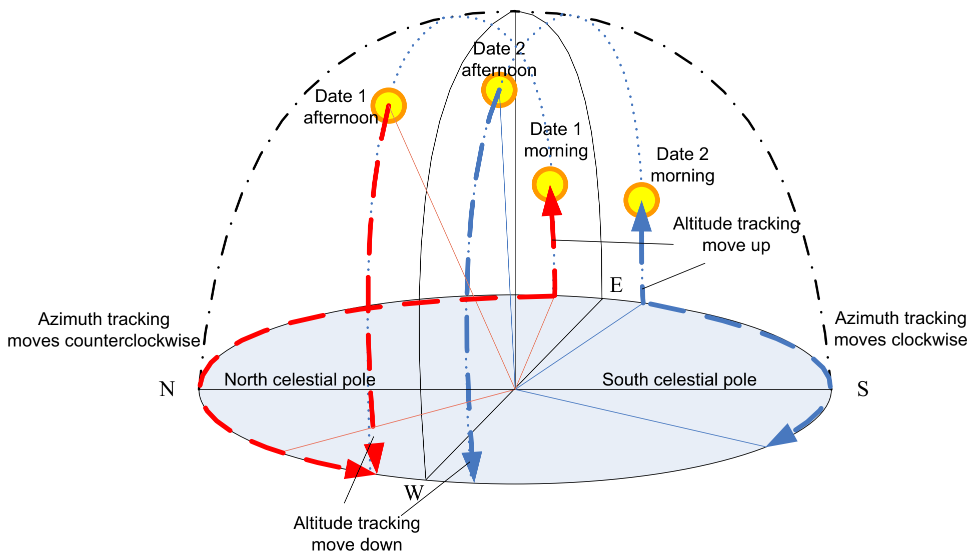


Fig. 5. Movement of tracking motors.

Table 1
Location of sun hourly.

	June 20, 2011		December 22, 2011	
	Altitude angle, α (°)	Azimuth angle, γ (°)	Altitude angle, α (°)	Azimuth angle, γ (°)
7:00 AM	−2.2	66.1	−6.5	113.0
8:00 AM	11.6	67.3	7.2	114.7
9:00 AM	25.3	67.1	20.5	118.0
10:00 AM	39.0	65.0	33.3	123.6
11:00 AM	52.2	59.5	45.1	132.8
12: 00 PM	64.2	46.7	54.7	148.3
1:00 PM	72.3	15.8	59.8	172.0
2:00 PM	70.6	332.0	58.4	198.8
3:00 PM	60.7	308.1	51.1	219.1
4:00 PM	48.2	298.3	40.4	231.6
5:00 PM	34.8	294.1	28.1	239.1
6:00 PM	21.1	292.7	15.0	243.6
7:00 PM	7.4	292.9	1.8	246.2

Table 2
Rated electrical output of solar module.

P_{max} (W)	38
I_{max} (A)	2.29
V_{max} (V)	16.60
I_{sc} (A)	2.59
V_{oc} (V)	22.20

Table 3
Measured electrical output of solar module.

P_{max} (W)	26.37
I_{max} (A)	2.04
V_{max} (V)	12.93
I_{sc} (A)	2.55
V_{oc} (V)	20.10

panels while the reading was recorded in every minute and stored. The tracking motors are programmed to work for a few seconds and idle for several minutes based on 1° of increment in altitude and azimuth angle. Based on these months, the calculated total energy consumed by both actuators in a day is 6.66×10^{-2} W h.

Based on the outdoor reading using a solar module analyzer, under an ambient temperature of 31.2 °C and solar irradiance of 840 W m^{-2}, the electrical output of the solar module is given in Table 3. The variations in the rated and measured electrical output are due to; the solar module performs at its best under standard conditions of cell temperature of 25 °C, air mass of 1.5 and irradiance of 1000 W m^{-2}. In addition, the performance of the solar module starts to deteriorate depending on the duration they are exposed to the sun. The field test results are divided into 3 groups according to the overall weather on a selected day; clear and sunny day, cloudy day, and heavy overcast and rainy day.

7.1. On a mostly clear and sunny day

In this climatic region, overcast is unavoidable. Even on a clear and sunny day, cloud formation is noticeable only the occurrence is at its lowest. During the day, solar irradiance reading shows a very smooth output power characteristic with a very little sudden drop due to cloud, as shown in Fig. 6.

Fig. 7 shows a comparison of the power output from the proposed approach and the fixed horizontal system. A very large improvement can be seen from the figure. The overall total generated power tracking solar module is 175.44 W h. The improvement is contributed from all parts where part A gave the biggest improvement by 256.97% due to the large incidence angle in a horizontal panel. Meanwhile, part C contributes in 195.56% of power gain, also due to a large incidence angle in horizontal panel, but due to several factors during this time period, the amount is lower than in part A. The factors namely are; afternoon atmosphere contains high water vapor and the ambient and solar panel′ s temperature is higher during the afternoon [35,36]. Part B still contributes about 52.49% power gain. In this case, the altitude angle difference of about 29–37º contributes to the improvement of generating power. In general, the maximum average of output generated from the tracking module in every hour of the day is significantly higher than in the fixed horizontal panel is given in Table 4, where the power gain from the tracker is 91.97%.

7.2. On a cloudy day

During the day, the solar irradiance showed a very frequent overcast, where during this overcast, the power drop to nearly zero for both panels. However, the hourly measured maximum average output power from solar tracking showed higher results than in horizontally fixed panel. Part B shows a period of time

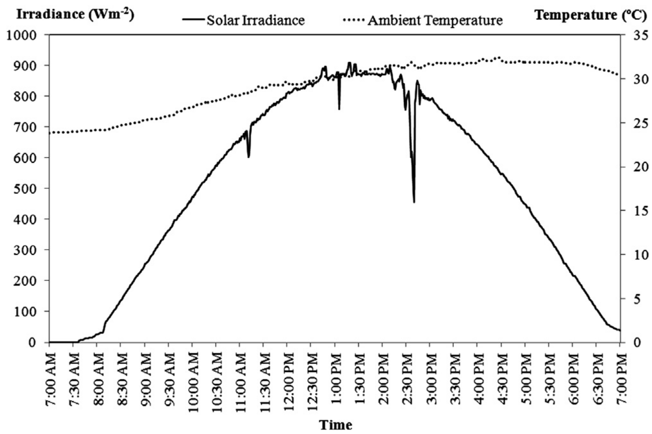


Fig. 6. Solar Irradiance and temperature on clear and sunny day.

Table 4
Measured maximum average output power at solar module during sunny day.

Time	P_{out} (W)	
	Sun tracking	Fixed horizontal
7:00 AM	0.01	0.00
8:00 AM	8.18	0.20
9:00 AM	17.31	1.36
10:00 AM	22.38	5.58
11:00 AM	24.96	11.54
12:00 PM	25.56	15.54
1:00 PM	24.76	16.58
2:00 PM	23.17	15.95
3:00 PM	19.50	11.18
4:00 PM	15.79	5.41
5:00 PM	10.49	1.24
6:00 PM	2.95	0.16
Average (W)	16.26	8.47

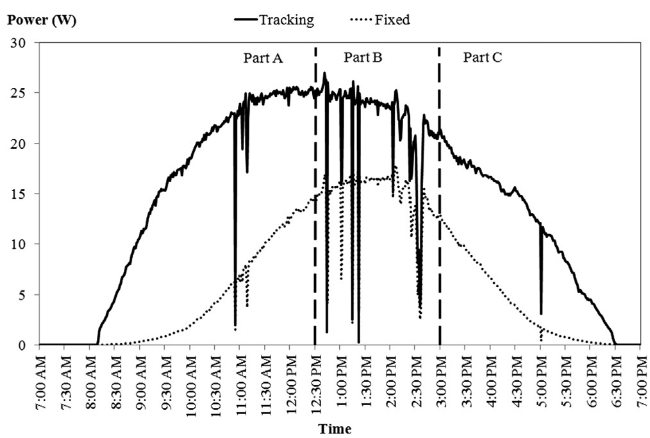


Fig. 7. Power on a mostly sunny and clear day.

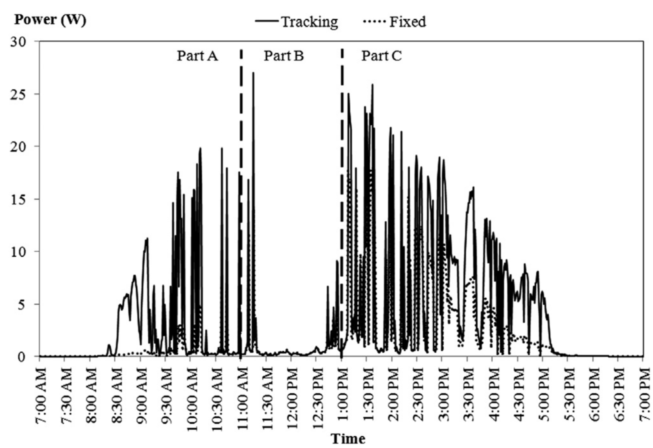


Fig. 8. Power on a cloudy day.

where the day experienced overcast where the power reading for both panels significantly dropped as a result of solar irradiance reading drops from 640 W m^{-2} to 200 W m^{-2} as given in Fig. 8. The generated power from tracking solar module for part A, B and C are 11.25 W h, 2.68 W h and 30.37 W h. However, it can be seen that, during these hours (11:00 AM–12:00 PM), the maximum average output power for a sun tracking panel is still higher than fixed horizontal panel as shown in Table 5. In part A, B and C the power gain from the solar tracker is larger than the fixed horizontal panel by 409.05%, 33.84% and 88.17%, respectively.

As for Part A and B, although the day experienced frequent overcast, the power reading in the measured maximum sun tracking panel is still significantly larger than a horizontally fixed solar module. In addition, the overall power gain for tracking panel compared to the fixed horizontal panel is high, with the value of 122.71%. The result shows that even during cloudy days, the tracking panel gave better power collection than a fixed horizontal panel, where the horizontally fixed panel is mostly affected by the cloudy conditions. However, compared to a mostly and clear day with a total of 175.44 W h, the power generated from the tracking panel is low with only 44.30 W h.

7.3. *On heavy overcast and rainy day*

On this day, the solar irradiance reading is low almost all the time, and the power collection is poor due to heavy overcast and rain. However, the overall power collection from solar tracker for one whole day is still better than in the fixed horizontal solar module by 90.42% as demonstrated in Fig. 9.

Table 5
Measured maximum average output power at solar module during cloudy day.

Time	P_{out} (W)	
	Sun tracking	Fixed horizontal
7:00 AM	0.01	0.00
8:00 AM	5.42	0.24
9:00 AM	9.78	1.13
10:00 AM	7.53	1.95
11:00 AM	2.52	1.63
12:00 PM	2.02	1.23
1:00 PM	17.26	11.64
2:00 PM	15.58	10.02
3:00 PM	13.96	6.87
4:00 PM	8.82	2.84
5:00 PM	1.78	0.50
6:00 PM	0.03	0.02
Average (W)	7.06	3.17

This is due to Part A contributes largely in the percentage of power gain. Based on the generated power gain of the solar tracker, part A, B and C contribute 208.57%, 47.03% and 12.04% and is larger by 6.57 W h, 4.91 W h and 0.36 W h, respectively from the horizontal panel.

On this day, during 4:00 PM to 6:00 PM, the hourly measure maximum average output power form fixed horizontal panel is higher than the sun tracking panel where during this time, it experienced heavy overcast and rain. Due to water vapor in the atmosphere, most of the direct irradiance became diffused and

the solar spectrums during afternoon worsened. Consequently, this led to a severe decrease in power, in which the tracker gave an even lower reading than horizontally positioned PV module as demonstrated in Table 6. This is because during severe overcast, direct irradiance is scattered to mostly diffuse irradiance and the best way to capture the isotropically-distributed diffuse solar irradiance emitted from the clouds during severe overcast is by orientating the PV module towards the zenith [37]. This showed that, in this climate, during heavy overcast and rainy day, the fixed horizontal solar module gives higher value than solar tracking panel.

In summary, persistent overcast skies cannot affect the open-loop system for the movement of controlling motors is limited by the programmed time. On a clear and sunny day, the solar tracker is at its top performance with 175.44 W h of generating power and 91.97% power gain compared to the horizontal panel as demonstrated in Table 7. During a cloudy day, the performance of horizontal panel is badly affected, in effect, a bigger difference between the tracking and fixed surface causes the power gain to be higher. Nonetheless, the value of generating power from the tracker for the day is only 44.30 W h, a value of 23.94 W h higher than a horizontal fixed panel. In addition, during a heavy overcast and rainy day, the power generated from the tracker worsen with only 28.42 W h of generating power.

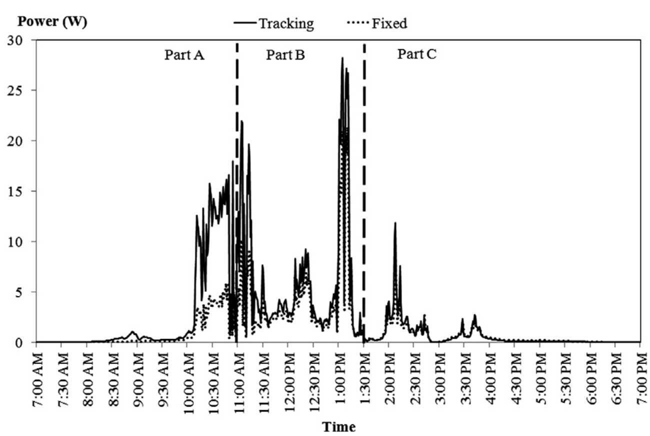


Fig. 9. Power on a heavy overcast and rainy day.

Table 6
Measured maximum average output power at solar module during heavy overcast and rainy day.

Time	P_{out} (W)	
	Sun tracking	Fixed horizontal
7:00 AM	0.02	0.01
8:00 AM	0.59	0.10
9:00 AM	0.48	0.22
10:00 AM	14.07	4.53
11:00 AM	10.18	5.09
12:00 PM	6.40	4.79
1:00 PM	12.55	6.96
2:00 PM	3.72	2.74
3:00 PM	1.30	1.16
4:00 PM	0.21	0.31
5:00 PM	0.13	0.17
6:00 PM	0.02	0.03
Average (W)	4.97	2.61

Table 7
Overall performance of tracker in different weather conditions.

	Generated power (W h)	Power gain (%)
Sunny and clear day	175.44	91.97
Cloudy day	44.30	122.71
Heavy overcast and rainy day	28.42	90.42

8. Conclusion

Solar tracking is a well known approach in achieving a higher power-generating capability. However, the high energy consumption of the driving system is its main drawback. Therefore, the energy efficiency aspect has been taken into consideration prior to the design where the tracker itself must provide an energy-saving feature. This research proposes a new design of well-improved structures for a stand-alone solar tracking system with a time and date-based controller. It has been confirmed that solar electricity generation using a solar tracking system in tropical climate is an appropriate solution to achieving higher energy output, as compared to a horizontal tilt solar system; this improved system was able to produce an output generation of up to 91.97% energy gain on a clear and sunny day compared to horizontally position PV module, particularly with the employment of time and date-based sun positioning system. This method clearly proved to be the better method as compared to the normal single axis tracking system and the fixed module. This is also a major finding which confirms that the two-axes solar tracking system is especially profitable in tropical-climate country like Malaysia, which experiences ample resource of sunlight. Results showed that even on a cloudy day and a severe overcast day, this tracking system still gave higher power gain for all-day performance. Moreover, the energy consumption of the system is fixed to only 4.97% of the energy produced in a highly potential day. Nonetheless, it can be improved if the tracker carries maximum number of panels with a higher power rating. Further improvements can be made to the system to enable higher power generation if the tracking system is connected in an array.

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